PAWS: Personalized Arm and Wrist Movements With Sensitivity Mappings for Controller-Free Locomotion in Virtual Reality

SOHAN CHOWDHURY, The University of British Columbia, Canada
WILLIAM DELAMARE, Univ. Bordeaux, Estia Institute of Technology, France
POURANG IRANI, The University of British Columbia, Canada
KHALAD HASAN, The University of British Columbia, Canada

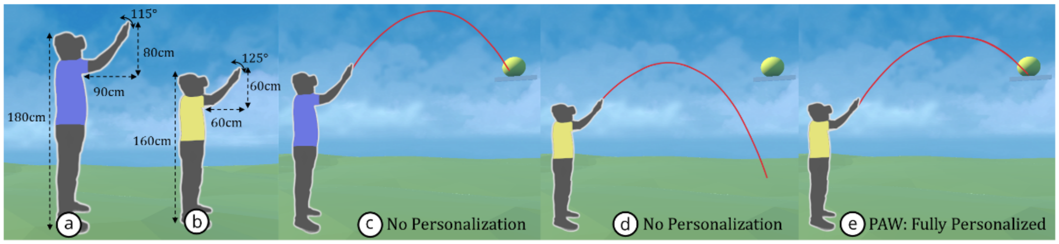

Fig. 1. (a-b) Two users with different physical attributes such as differences in height, arm reach (horizontal and vertical) and wrist angle range. (c) Users with specific physical attributes might find it easy to teleport, (d) while users with different physical attributes might find it difficult. (e) Our proposed a personalized teleportation technique PAW that takes differences into account and personalizes the teleportation parabola so that every user, regardless of their physical attributes, can perform the teleportations easily.

Virtual Reality (VR) headsets equipped with multiple cameras enable hands-only teleportation techniques without requiring any physical controller. Hands-only teleportation is an effective alternative to controllers for navigation tasks in virtual reality - allowing users to move from one point to another instantaneously. However, the current implementation of hands-only techniques does not consider users' physical attributes (e.g., arm's reach). Thus, a hands-only teleportation technique can lead to different user experiences based on physical attributes. We propose PAWS, a personalized arm and wrist-based teleportation technique that incorporates users' physical attributes for improved teleportation experiences. We first evaluate different degrees of teleportation personalization with no-, partial, and full personalization. We find that full personalization offers faster locomotion – but at the cost of degraded performances with distant targets due to increased sensitivity. We hence further explore different combinations of mapping functions (e.g., sigmoid, quadratic) to personalize motor movements and find that asymmetric functions result in improved performance. Overall, our results show that PAWS helps users to navigate quickly in virtual environments.

CCS Concepts: • **Human-centered computing** → **Virtual reality**; *User studies*; Pointing.

Authors' addresses: Sohan Chowdhury, The University of British Columbia, Okanagan, BC, Canada, sohanchy@student.ubc.ca; William Delamare, Univ. Bordeaux, Estia Institute of Technology, Bidart, France, w.delamare@estia.fr; Pourang Irani, The University of British Columbia, Okanagan, BC, Canada, pourang.irani@ubc.ca; Khalad Hasan, The University of British Columbia, Okanagan, BC, Canada, khalad.hasan@ubc.ca.

2573-0142/2023/9-ART217 $15.00
https://doi.org/10.1145/3604264

Additional Key Words and Phrases: Locomotion, Teleportation, Personalization, Virtual Reality, Arm, Wrist

ACM Reference Format:
Sohan Chowdhury, William Delamare, Pourang Irani, and Khalad Hasan. 2023. PAWS: Personalized Arm and Wrist Movements With Sensitivity Mappings for Controller-Free Locomotion in Virtual Reality. *Proc. ACM Hum.-Comput. Interact.* 7, MHCI, Article 217 (September 2023), 21 pages. https://doi.org/10.1145/3604264

1 INTRODUCTION

With the recent availability of on-device hand-tracking solutions in VR headsets, hands-only teleportation is becoming a viable controller-free alternative. Hands-only methods relieve the user from having to hold a controller allowing natural and rapid input (i.e. without needing to strap on a device). Prior work has shown that such methods are intuitive and easy to use for VR interaction and offer a rich design space [6, 11, 28, 44]. Consequently, researchers explored different hands-only teleportation solutions leveraging hand movements [27, 30, 44, 51] to navigate from one location to another in virtual environments. Results show that bare-hand techniques leads to less motion-sickness and lower task loads than controller-based techniques, while still providing intuitive and immersive experiences [30, 38].

Teleportation is already the default and primary locomotion technique in most commercial VR games, applications and SDKs, especially for small play environments [10, 17, 47]. Though hands-only teleportation pointing can be considered as a potential alternative to controllers, it has an inherent dependency on users' physical attributes such as arm flexibility, wrist flexibility, and range of movements. For instance, arm and wrist movements are leveraged in hand-based techniques to control the teleportation pointer [6, 44]. However, the comfortable maxima and minima of arm movements (dependent on arm span and shoulder flexibility) and wrist angles can differ from user to user [41, 42]. Thus, different people may experience the same hands-only teleportation technique differently based on their physical abilities and attributes (Figure 1c, d).

Personalization and adaptation of techniques according to users' attributes have been explored for various interactions such as cursor control in 2D interfaces [26], prototyping user interfaces for Augmented Reality [7], generating custom game scenarios for Virtual Reality [40] and as a general UI consideration [1, 20, 21, 32, 33]. Adapting techniques to users' physical and/or perceptual characteristics can lead to improved performances [29] and usability [26]. Although personalized applications exist for VR contexts, to the best of our knowledge, no prior work explored leveraging personalized arm and wrist movements to help users navigate in VR. This work is motivated by the research hypothesis that personalization can be beneficial (regarding both user performances and preferences) for teleportation. However, there are some gaps in previous work we need to explore to validate this hypothesis, leading to two research questions:

- **RQ1:** To which extent should the technique be personalized? In other words, which combination of physical attribute(s) involved in hands-only teleportation result in improved performances when personalized?
- **RQ2:** How should the personalization of motor movements be remapped to the personalized motor ranges?

We report on two user studies exploring the research hypothesis and our two research questions (RQ1 and RQ2) regarding the benefits and drawbacks of teleportation personalization. The first user study addresses RQ1 to explore possible combinations of physical attributes available for personalization. We investigate and compare no-personalization, partial personalization (i.e., only arm vertical range), and full personalization (i.e., wrist and arm ranges personalization). Results reveal that users are faster with full personalization than with the other two techniques (RQ1). However, with all techniques, there is an increase in sensitivity due to the re-mapping of the motor range, and performance degrades for distant targets. This effect is due to reduced motor stability and control in poses required to reach such distant targets. We hence perform a second user study to address RQ2 to further explore different sensitivity mapping functions (e.g., sigmoid, inverse-sigmoid, quadratic) for three movement ranges: arm extension/retraction range, arm vertical movement range and wrist extension/flexion range. Each sensitivity function combination leads to the parabolic pointer movement becoming more or less stable (i.e., precise or coarse) in response to hand movements in different ranges of movements. Results show that users' teleportation performance improved when using adapted sensitivity mapping functions: sigmoid or inverse sigmoid mappings for arm vertical and flexion/extension movements, and a quadratic mapping for wrist movements.

Our contributions include: (i) PAWS - a personalized arm and wrist-based teleportation technique for virtual environments; (ii) A performance comparison of different teleportation techniques varying the degree of personalization; (iii) An exploration of different mapping functions to remedy increased sensitivity due to personalization;

2 BACKGROUND AND RELATED WORK

Our work builds on previous research on teleportation, hands-only locomotion, and personalization techniques. We investigate hands-only teleportation since the next-generation of head-mounted displays [2, 48] include hands-only controls, hence warranting further investigation into this form of input for locomotion as it is a crucial part of VR. Thus, we focus on the parabolic pointer teleportation technique - the de-facto standard in most commercial controller-based applications and used in previous work [3, 10, 17]. We present an overview of the prior work in these related areas.

2.1 Teleportation

Two common types of locomotion are widely explored in prior work: continuous and instant. With a continuous locomotion technique, users move to their destination while simulating a real-world movement such as walking, flying, or being in a vehicle. On the other hand, with an instant locomotion technique, users instantly move to the destination, removing the intermediate steps and movements. Teleportation as an instant locomotion method for VR was first introduced by "The Jumper Metaphor" [4]. With Jumper, users are automatically teleported to the destination they are looking at after a certain amount of time. "Point and Teleport" [6] allows an explicit destination selection by allowing users to aim in the environment with a straight line-based pointer. The system performs the teleportation after pointing at a specific point for a pre-defined amount of time. When comparing teleportation to prevalent VR locomotion techniques such as "Walking in Place" [45] and traditional joystick controllers, researchers showed that teleportation caused significantly less VR sickness, was easy to understand, was preferred by users, and caused less fatigue than the other techniques [5, 6]. The reasons for the popularity and the widespread acceptability of teleportation are manifold. Indeed, teleportation provides high levels of enjoyment and presence, low discomfort [18], is easy to use and is highly preferred by users [5]. Additionally, the non-continuous nature of a teleportation results in users experiencing very little VR sickness [18, 34] while maintaining an acceptable level of spatial awareness. Though a straight line pointer was used in "Point and Teleport", the curved parabolic pointer has become standard for locomotion in commercial and general-purpose VR applications and games [19, 34]. Willich et al. [49] explored various foot based techniques to control the parabolic teleportation pointer using the foot's 3D position and applied pressure on the sole of the foot. The authors noted that controller-free teleportation was an important area for exploration as it allowed users to perform natural hand interactions in VR. The parabolic pointer provides a visual indication of the possible destinations by always landing top to bottom on a plane. This provides an intuitive understanding of the topography to the user [15]. It is the default teleportation pointing method with most VR software development kits [36, 37, 47].

2.2 Controller-Free Locomotion

Recent works have explored hand-only interaction for teleportation with hand-tracking capabilities. Mine et al. [35] proposed one of the first hand-based works, with techniques designed to control the motion direction via users' hand position and orientation. The authors noted that mapping physical motion (e.g., hand movement) to virtual movement is one of the most intuitive means of transportation through a virtual world. Similarly, Chastine et al. [9] explored a locomotion technique allowing users to navigate in VR using the relative distance between their palm and a leap motion device. They noted that users could intuitively use controller-free techniques without little to no training, even though hardware-based techniques performed better in accuracy. Ferracani et al. [16] designed and compared four controller-free techniques, with two gesture-based locomotion techniques named "Tap" and "Push". Authors compared Tap with other locomotion techniques such as Walking-in-place where users move their legs up and down in walking motion, yet remaining in the same spot [45] and Swing where users swing their arms beside their body similar to jogging [38]. Results revealed that pointing with Tap provided higher accuracy, lower fatigue and higher perceived immersion than the other techniques.

Instant locomotion has mostly been explored for controller-based applications [10, 17] while hands-only implementations have not been as thoroughly explored. With "Point and teleport", user points their index finger to the target destination [6]. Authors showed that the technique requires less cognitive load and was more usable and user-friendly than physical controllers (i.e., joystick). Schafer et al. [44] explored single-handed and two-handed gestures and timeouts for teleportation confirmation, not for the control of the parabolic pointer ray. Results from a user study showed that their teleportation had a high level of usability and offered ease of use. For WriArm [11], researchers explored using combined wrist and arm movements for hands-only teleportation with separate gestures for each action. They investigated a combination of wrist and arm movements to control the parabolic pointer and showed that WriArm provided faster teleportation than arm based techniques. Since previous works already establish the usability and benefits of hands-only locomotion as an alternative to controllers, we focus on hands-only locomotion.

2.3 Interaction Personalization

Arazy et al. [1] defined the term "personalization" as an effective way to accommodate individuals' differences into the design of user interfaces. For example, recommending content, tailoring user interfaces, or adapting the behaviour of a system to match the user's needs - thus supporting personalization [26, 33, 40]. Differentiating between calibration and personalization is a terminology interpretation of: while both attempt to improve the user experience by making the system more effective, personalization focuses on individualizing the experience for each user, while calibration focuses on optimizing the system's performance (usually accuracy or precision) overall. For instance, Hammond et al. [33] showed that users prefer personalized pointing techniques for web navigation. More specifically, users prefer a system that adapts to pointer movements over time while also considering user preferences to overcome any physical limitations. Hourcade et al. [26] showed that adapting the pointing speed according to users personal abilities improved pointing accuracy and intuitiveness, with children and adults benefiting the most when navigating the web in 2D interfaces. Broll et al. [7] analyzed the requirements for AR applications from different user groups and found that a single user interaction technique cannot satisfy every user's needs. They hence recommend designing personalized interfaces for augmented reality. Martín et al. [32] conducted design sessions with older and younger adults with accessibility issues such as limited hand dexterity. They showed that personalization or adaptation is critical to prevent certain groups from being disadvantaged by the system. In "Tailored Virtual Reality" [40], authors present user-tailored VR exercises for smart physiotherapy and show that personalized VR applications provide better understanding and motivation for users to continue using the application. From these previous works, it can be identified that users with varying physical attributes require systems to be adapted and personalized for equal usability. As a result, we explore personalizing hands-only teleportation, as it would allow every user an equal experience in the exploration of virtual worlds. In a recent work, Chowdhury et al. [11] explored wrist and arm-based teleportation without considering differences in physical attributes (e.g., arm length) and suggested future investigation considering users physical attributes.

With hand-tracking, the differences in physical attributes and motion range become more apparent as some users face disadvantages and require longer times traversing heights or distances. We explore solutions improving upon parabolic teleportation for bare-handed VR to reduce such issues.

3 HANDS-ONLY PARABOLA POINTER CONTROL

3.1 Components to control a parabolic pointer

Users should be able to manipulate four components to fully control a parabolic pointer: the origin, the direction, the launch angle, and the distance. These components can be controlled with solely hand- and wrist-based movements. The *Origin and Direction* and *Launch Angle* of our technique are similar to *Point and Teleport* [6] and *WriArm* [11].

- **Origin and Direction** (Figure 2a): Intrinsic to mid-air pointing techniques, the parabolic ray starts from the user' hand. Casting direction mainly relies on arm and wrist orientation [5, 11, 12, 30, 51]. The arm provides coarse, rapid and large pointer movements, and the wrist offers more control for precise pointer movements.
- **Launch angle** (Figure 2b): The parabola's launch angle is fully controlled by the wrist's upward/extension and downward/flexion movements.
- **Distance** (Figure 2c): The distance traveled by the parabola can be computed from the force a projectile would be launched from the origin on a given launch angle. We introduce "force-control", which allows users to operate on the parabolic end-point distance by modifying the "force" used to compute the parabola. Users decrease or increase the distance of the parabola's end-point by retracting or extending their arm respectively. Allowing users to control the force of the parabola - and hence the traveled distance - is similar to Skyport (for mid air targets) [34]. We included this feature as we saw in our pilot that along with wrist movements, force-control

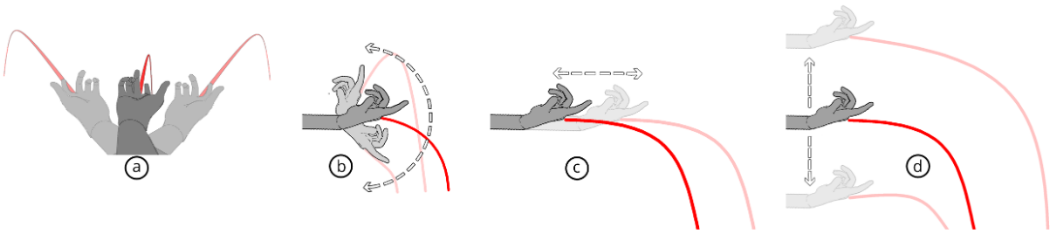

Fig. 2. (a) A user can control the ray origin and direction via arm and wrist orientation. (b) Launch angle is controlled by the wrist's upward/extension and downward/flexion movements. (c) The user can reach a further distance via arm extension and retraction movements, and (d) by moving their hand vertically up or down.

allows users to avoid going to extreme wrist angles for difficult destinations by increasing or decreasing the force.

However, the distances and heights users can reach with teleportation are different for users with different arm lengths, flexibility of arm movement (extension and vertical ranges), and/or flexibility of wrist movement. To provide a similar experience to every user and remove this bias, we next discuss the need to personalize the interaction input based on users physical attributes. This would ensure that all users can have similar teleportation experience regardless of their physical attributes. For example, if a user can only tilt their wrist to a minimum of -50° and a maximum of 50° whereas navigating the environment requires to reach a minimum and a maximum of -75° and 75°, then their [-50, +50] range can be mapped to the [-75, +75] range in the technique.

3.2 Levels of Personalization on Teleportation

With arm and wrist movements, attributes that can be personalized are: the arm extension and retraction range to manipulate the distance via the "force-control" mechanism (A_{dist}), the arm vertical movement range to control the origin (A_{ori}), and the wrist upward/extension and downward/flexion range to control the launch angle (W_{angle}). However, it is not clear if *all* these attributes warrant a personalized counter-part, or only a combination of them. We can have the following attribute combinations:

- One attribute personalization (A_{dist}, A_{ori}, or W_{angle}),
- Two attributes personalization ($A_{\text{dist}} + A_{\text{ori}}$, $A_{\text{dist}} + W_{\text{angle}}$, or $A_{\text{ori}} + W_{\text{angle}}$),
- all three attributes personalization ($A_{\text{dist}} + A_{\text{ori}} + W_{\text{angle}}$).

To reduce the number of combinations, we ran a pilot study to exclude options which did not bring any noticeable improvement. As a result, we narrow down our exploration to three candidates: the baseline (standard arm and wrist movements), baseline + Personalized A_{dist} (PAdist), and fully Personalized $A_{\text{dist}} + A_{\text{ori}} + W_{\text{angle}}$ (PAW).

- Baseline: The baseline is set from generic users who can reach targets inside a 12m^3 box. The **origin and the direction** of the parabola follow a 1:1 (absolute) mapping with the hand's location and orientation. The standard comfortable arm vertical range - without personalization - is set to [-0.4 m, +0.5 m] from the headset. The arm flexion/extension movements control the **distance**, i.e., the force at which the parabola is ejected (originally constant, F = 12 m/s). The standard comfortable arm flexion/extension range - without personalization - is set to [0.11 m, 0.6 m], corresponding to a force in the range F = [1, 12]. The wrist angle is used to control the parabola **launch angle**. When the wrist is parallel to the ground, the parabola is launched at 0° (i.e., base position). The angle of the wrist is calculated as the angle of the wrist from this base position. The user can move their wrists upward (i.e., extension), and downward (i.e., flexion) to control the launch angle. The standard comfortable wrist flexion/extension range - without personalization - is set to [-55°, +70°].
- Personalized Arm (PAdist): The horizontal and vertical movement range of the arm also has an effect on the parabola's origin and direction and the force-control mechanism, resulting in different minimum and maximum parabola distances for different users. We used the distance between the wrist and the body (i.e., via the HMD position) to measure horizontal and vertical arm extensions and retraction. Before using the system, users extend and retract their arm to comfortable maximum and minimum distances. These minimum and maximum values were recorded and then used by the system to adapt the force so that the minimum and maximum force values (i.e., [1, 12] in our settings) could be achieved by the user. If the user arm extension/retraction value falls between Arm_{Max} and Arm_{Min}, and the force falls between Force_{Max}

and Force$_{Min}$, we use the following linear formula:
$Y = (X - Arm_{Min})/(Arm_{Max} - Arm_{Min}) * (Force_{Max} - Force_{Min}) + Force_{Min})$

- Fully Personalized Arm and Wrist (PAW): Before using the system, users aim towards high and low destinations for the system to record their maximum and minimum wrist angle and arm vertical ranges. Similarly, users also extend and retract their arm to comfortable maximum and minimum distances. The system then considers these three comfortable ranges instead of the three standard ranges used by the baseline.

The baseline parameters need to reflect users with average height and arm length as they are correlated[42] and strongly influence users' teleportation performances. The comfortable standard values were estimated by taking averages from multiple people (N=3) around the average male height (178 cm) for the local country [14] who were able to navigate the environment comfortably. For all techniques, to improve the usability of the parabolic pointer, we use Kalman filters to increase the pointer stability. Similar to other works dealing with the same effect during pointing [50], we add a last-second spike compensation when performing the confirmation gesture to avoid any instability caused by unintended trigger movements. When the gesture is performed, the system immediately analyzes the last 30 frames of pointer locations to detect any abrupt or sudden changes (i.e., spikes) in the pointer location. If such a spike is found, the location before the spike is used for selection. .

4 STUDY 1: EXPLORING DIFFERENT LEVELS OF PERSONALIZATION ON TELEPORTATION

The goal of this study is to explore whether there are certain personalized combinations of physical attributes that provide more benefits than others (RQ1).

4.1 Participants

We recruited 12 right-handed participants (8 male) with a height of 165 cm and below (mean height = 162.5, SD = 3.5), ages 19 to 35 (mean age = 24.3, SD = 4.1). The system recorded average arm vertical range from -0.40m (SD = 0.09) to 0.32m (SD = 0.14) and average arm horizontal range form 0.19m (SD = 0.37) to 0.51m (SD = 0.06). The baseline users ranges reported in section 3.2 and these values are both reported from a reference point of the headset as the camera based hand tracking setup on the Quest 2 does not support tracking the shoulder. Participants were recruited using on-campus flyers and word-to-mouth, and received $15 as honorarium for participating in the study. Eight of the 12 participants had prior experience using VR. All eight participants were familiar with controller-based teleportation.

4.2 Apparatus

We used the Oculus Quest 2 VR headset for its built-in cameras and the Oculus Hand Tracking SDK for hand tracking instead of marker-based or external motion tracking solutions. Unity 3D (2020.3.33f1) was used for the primary development software along with C# scripting to design and develop the techniques and the virtual environment. We used the MRTK SDK to access real-time tracking data on key points on users' hands such as their palm and finger joints. Oculus Wireless Link was used for rapid development on a computer with RTX 3070 GPU. Note that the user study was conducted solely on the Quest 2 headset itself, without any connections to computer, representing real-world usage. The data logged during study sessions was automatically transferred from the headset to a Cloud-Firestore database.

4.3 Experimental Task, Procedure and Design

4.3.1 Task. Participants performed teleportations to a set of destinations for each technique as shown in Figure 3. For our controlled in-lab evaluation, we bound teleportation possibilities to (i) platforms via (ii) a single move.

- Platforms: this choice allows us to precisely control each teleportation distance and elevation [10]. Even though in teleportation, the user instantly moves to the destination, we provide users with a place to stand on rather than suspend in mid-air. Platforms fit a metaphor of terrain-based elevation changes while limiting navigation options to our pre-determined experimental conditions (distance, height).
- Single move: this choice also allows us to precisely control experimental conditions in order to generalize conclusions. Indeed, it would not be possible to conclude on far teleportations if users chose to perform multiple close moves for instance. Enforcing one teleportation per trial provides the option to cover all conditions while still allowing extrapolations of real conditions (e.g., if users prefer to perform several teleportations for far away targets, we have data for close distances). Additionally, this reduces participants disorientation during the experiment [6, 19].

Each destination was marked with red semi-transparent sphere of 0.5 meter diameter placed on top of a 1-meter square meter platform. A downward arrow was placed above the sphere to facilitate the target search in the VR environment. Only one target destination (i.e., platform, arrow and the sphere) was visible to the user (Figure 3a) without any occlusion. The color of the sphere and the parabolic pointer change from red to green participants aim the pointer at the sphere, visually showing that are correctly aiming at the target (Figure 2b). Participants can use a hand gesture from the MRTK SDK [43] (i.e., closing their index finger) to teleport to the target platform. Note that issuing confirmation gestures to a non-platform was disabled during the study and recorded as an error, similar strategies are used to restrict users from teleporting to out-of-bound areas in VR games [46]. Once participants issued a confirmation gesture to the target sphere, audio feedback was provided indicating successful teleportation. The next destination appeared only after a successful teleportation (Figure 3b). In summary, each teleportation required finding the next destination target, aiming at it, and confirming the teleportation. We define the set of destinations by considering two main aspects: distance from users, and height variation from their current elevation. The angle at which the target appeared was randomized between -45° and +45°, alternating between positive and negative angles for every target to reduce directional bias and ensure that no two consecutive teleportations were placed in the same direction.

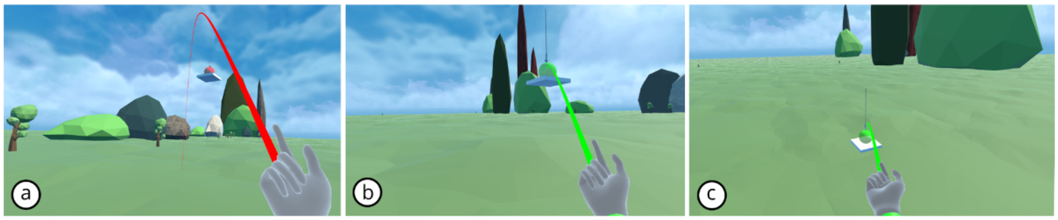

Fig. 3. Teleportation with *Height variation* and *Distance* factors. (a) A user controls the pointer with arm and wrist movements (*Height variation*: from 0m to 5 m and *Distance*: 10.5 m). (b) The color of the parabolic pointer and the sphere changes from red to green once participants successfully aim the pointer at the sphere (*Height variation*: from 0 m to 2.5 m and *Distance*: 7.0 m). (c) The user is teleported to the target platform once they issue a hand gesture for selection (i.e., closing their index finger) and looks down to the next target location. (*Height variation*: from 5 m to 0 m and *Distance*: 3.5 m)

- **Distance**: Previous work focusing on 3D teleportation used different distance ranges, such as 7 m and 14 m [34], 10 m [44], or 2 m and 4 m [19]. Note that our task is different since we also vary elevation, which has not been investigated yet in combination. We hence ran a pilot study where we observed that users could teleport up to a 10.5 m distance when the targets were elevated. Therefore, we included 3.5 m, 7.0 m and 10.5 m as teleportation distances, which covers the range [3.5 m, 11.6 m] when considering both target distance and elevation (i.e., leading to diagonals longer than the distance alone).
- **Height variation**: We define height variation as the height difference between the current user position and the target location. This variation can be positive (target on a higher level than the user) or negative (target on a lower level than the user). Matviienko et al. [34] recently considered vertical heights without varying distances: destinations targets were positioned only vertically (up or down). In our study, we consider the combination of height variation and distance similar to WriArm [11], leading to more realistic destination placements while ensuring fully controlled settings. Our initial pilot study showed that, with our 10.5 m maximum distance, an elevation of 5 m is a comfortable maximum height difference for a maximal diagonal distance of 11.6 m. We hence consider elevations of 2.5 m and 5 m, leading to planar trajectories (from 0 m to 0 m), upward trajectories (from 0 m to 2.5 m or 0 m to 5 m), and downward trajectories (from 2.5 m to 0 m or 5 m to 0 m) for height variation.

4.3.2 Procedure. During the study, each participant wore the Quest 2 headset without controllers, and stood in an empty 2×2 meter space. Participants started with a brief introduction to VR, locomotion, teleportation, and the study itself including explanations of each technique. With each technique, participants first performed 30 practice trials. Then they performed two blocks of 45 trials (i.e., 3 *Distance* × 5 *Height variation* × 3 repetitions), with a 2 minutes break in-between blocks to avoid arm fatigue. After completing the 90 trials, we asked participants to remove the headset to get a seated 3-minute break. During each break we asked the participant for their perceived VR sickness on 20 point scale [34]. We repeated this process with the next *Technique* for all three techniques. Each participant completed 3 *Techniques* × 3 *Distance* × 5 *Height variation* × 3 repetitions × 2 blocks for each technique = 270 trials. After the experiment, participants filled out a questionnaire to collect demographic information and feedback on each *Technique*. Collecting feedback after finishing all the combinations allows participants to compare and contrast the techniques [22, 23, 39]. Each session lasted between 45 minutes and 1 hour.

4.3.3 Design. We used a within-subjects design with *Technique* as the primary independent variable with 3 levels (*Baseline*, *Personalized Arm Force Control (PAdist)*, and *Personalized Arm and Wrist (PAW)*). The order of *Technique* was counter-balanced across participants using a balanced Latin square. We also consider *Distance* (3.5 m, 7.5 m,11.5 m) and *Height variation* (from 0 m to 0 m, from 0 m to 2.5 m, from 0 m to 5 m, from 2.5 m to 0 m and from 5 m to 0 m). Distance and Height were presented randomly for each technique.

The primary measures computed from logs were *Trial Time* and *Error Rate*. *Trial Time* is the time taken to teleport to a destination. Participants are required to teleport to a 'start' platform at the beginning of each technique. After teleporting to this 'start' platform, a trial begins and the timer starts (i.e., start time). Once they teleport to the next platform, the timer stops (i.e., end time). We subtract the start time from the end time to calculate the trial time. Note that once the timer stops, a new timer starts to record the start time for the next teleportation. This is repeated for each destination to measure the trial time of each teleportation. *Error Rate* is amount of times the user tried to teleport while not correctly selecting the destination. We also collected subjective measures via questionnaires. In summary, we had: 3 *techniques* × 3 *Distances* × 5 *Height* × 6 repetitions = 270 trials per participant.

4.4 Results

4.4.1 Trial time. We use a repeated measures ANOVA and post-hoc pairwise comparisons to analyze the mean trial time. We add Cohen's d for reporting the effect size for pairwise comparisons and use the following values for the interpretations of the different effect size: 0.2 for small, 0.5 for medium and 0.8 for large - as suggested by Cohen [13]. *Technique* has a significant effect ($F_{2,22} = 7.70$, $p < 0.01$, $\eta^2 = 0.41$) (Figure 4a). Users are significantly faster with PAW (mean 2.56s, SE 0.13) than PAdist (mean 2.74s, SE 0.13, Cohen's d 0.41) and Baseline (mean 2.85s, SE 0.10, Cohen's d 0.70). Results also reveal that *Distance* has significant effects on trial time ($F_{2,22} = 38.30$, $p < 0.001$, $\eta^2 = 0.77$): Users are significantly slower with targets located at 10.5 m (mean 3.05s, SE 0.13) than with targets located at 7.0 m (mean 2.60s, SE 0.11, Cohen's d 1.15) and 3.5 m (mean 2.50s, SE 0.11, Cohen's d 1.33) from the user. We also observe a significant effect for *Height variation* on trial time ($F_{4,44} = 38.72$, $p < 0.001$, $\eta^2 = 0.78$). Post-hoc pairwise comparisons between *Height variation* show that users are significantly slower for navigating to extreme upward trajectories (i.e., from 0 m to 5 m), with a mean trial time of 3.40s (SE 0.14), than when teleporting to other height variations. We also observe similar results for extreme downward trajectories: going from 5 m to 0 m (mean 2.77s, SE 0.13) is significantly slower than other height variations except for the upward height variation from 0 m to 2.5 m. Results also reveal that navigating from 0 m to 2.5 m (mean 2.65s, SE 0.12) is significantly slower than going to a planar trajectory (from 0 m to 0 m, mean 2.38, SE 0.10, Cohen's d 0.70). Though we didn't observe any interaction effect *Technique* × *Height variation* ($F_{8,88} = 0.90$, $p = 0.52$), *Technique* × *Distance* ($F_{4,44} = 1.42$, $p = 0.24$) we notice interaction effect for *Height variation* × *Distance* ($F_{8,88} = 13.27$, $p < 0.001$). In addition, the trial time differences between height changes disappear with increased distances, except for the highest height change (from 0 m to 5 m), which remains significantly slower than all others across all distances. the main source for the overall poor performance across different distances.

4.4.2 Error Rate. We use Friedman tests with Wilcoxon tests for post-hoc pairwise comparisons to analyze error rates (Figure 4b). The overall error rate is 15.57%. There is no significant difference in error rates regarding *Technique* ($\chi^2(2, N = 12) = 2.68, p = 0.26$) and *Height variation* ($\chi^2(4, N = 12) = 8.99, p = 0.06$). *Distance* has a significant effect on error rate ($\chi^2(2, N = 12) = 12.81, p < 0.05$). Pairwise comparisons show that close distances (mean 12%) lead to significantly fewer errors than mid (mean 17%) ($z = -2.35, p < .01$) and far distances (mean 18%) ($z = -2.93, p < .01$). We observe interaction effect for *Height variation* × *Distance* ($F_{8,88} = 2.42$, $p < 0.05$). Similar to the trial time,

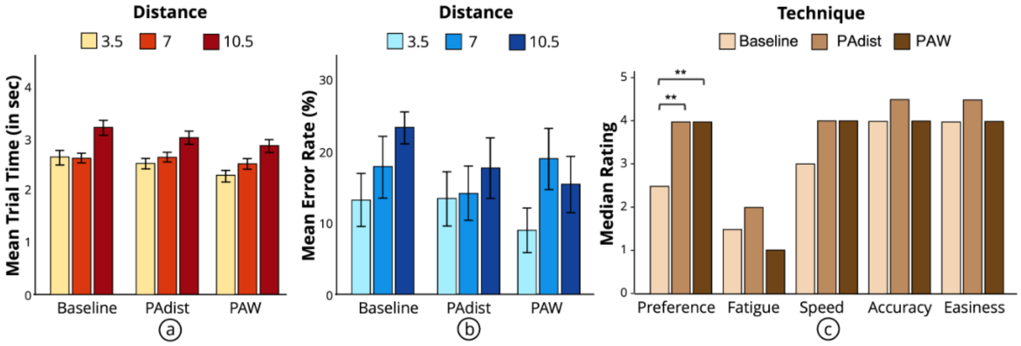

Fig. 4. Mean (a) trial time and (b) error rate across the techniques. (c) Users ratings on baseline, PAdist, and PAW based on their preference, fatigue, speed, accuracy and easiness. Error bars show the 95% CIs.

we notice that differences between error rates disappear with increased distances. There are no interaction effect for *Technique* × *Height variation* ($F_{8,88} = 0.58, p = 0.79$) and *Technique* × *Distance* ($F_{4,44} = 1.69, p = 0.17$).

4.4.3 Preference Scores and Subjective Feedback. We collected users feedback on their preference, fatigue, speed, accuracy and easiness on a 5-point Likert scale for each technique. We perform our analysis with Wilcoxon Signed Ranked Tests. Figure 4c shows the median ratings for *Technique*. We observe that *Technique* has a significant effect on users' preference ($\chi^2(2, N = 12) = 12.05, p < 0.01$). PAW and PAdist, both with a median rating of 4, are significantly different from the baseline (median 2.5) on users' preference ($z = -2.44, p < 0.05$ and $z = -3.17, p < 0.01$, respectively). There is no other pairwise statistically significant differences. However, we observed favorable mean user ratings with PAW and PAdist for all other categories: fatigue (PAW 1.58 vs. PAdist 2.08 vs. baseline 2.25 where a lower value indicates less arm fatigue), speed (PAW 4.00 vs. PAdist 4.08 vs. baseline 3.08 where a higher value suggests a faster technique), accuracy (PAW 4.25 vs. PAdist 4.17 vs. baseline 3.50 where a higher value indicates a more accurate technique) and easiness (PAW 4.25 vs. PAdist 4.17 vs. baseline 3.67 where a higher value indicates an easier technique). No notable VR sickness was reported by participants for any of the techniques. Participants also provided positive feedback on both personalized techniques, PAW and PAdist. For instance, participants commented that both *"PAW and PAdist performed better than the baseline"* [P11], and that they felt *"more comfortable"* when using PAW [P5, P7]. However, they expressed that destinations were challenging to reach due to the sensitivity of the pointer. Thus, we next explore different sensitivity functions allowing a more fine-grained pointer control.

4.5 Discussion

RQ1: *To which extent should the technique be personalized?*
Users are significantly faster with full personalization, when all three attributes are personalized (i.e., PAWS) than partial with personalization (i.e., PAdist) and with no personalization (i.e., baseline). This is also reflected in users' subjective ratings revealing preference for personalized techniques – PAWS and PAdist. This shows that PAWS helps users with limited arm movements and wrist flexion/extension abilities.

Results also indicate that reaching distant and elevated targets is more difficult than in other locations. This is primarily due to distant and elevated targets while requiring users to reach their maximum comfortable ($A_{\text{dist}}, A_{\text{ori}}, and W_{\text{angle}}$) ranges. These maximum ranges offer less control and stability, which is also explained by the relatively high error rates for these distant targets. This warrants further investigation to explore solutions to counteract the reduced control and stability for these target locations.

5 STUDY 2: EXPLORING SENSITIVITY FUNCTIONS

Our first study explored personalizing the parabola controls based on individual physical attributes. Using personalized arm and wrist movements ranges effectively allowed a user to teleport faster than no personalization. However, we noticed that there was a performance degradation for difficult-to-reach targets located to a distant and highly elevated platform. We observed that these difficult to reach destinations usually required large arm extension and wrist angles, which create body postures inadequate for precise and stable movements. Users with a lower range of motion for one or more attributes face an increased sensitivity as a trade-off. This is intuitive as controlling a large movement range using a smaller available range will result in some loss of fine-grained control. Previous work has shown that different sensitivity curves [41] can provide additional benefits for such motor movements (e.g., wrist movement).

In this follow-up study, we evaluate the effectiveness of mapping functions (RQ2) that consider the associations between motor movements and sensitivity as a remedy to the sensitivity trade-offs of personalization. We explore several sensitivity functions and their combinations tailored to the PAW technique. Recall that PAW uses three movement ranges that can be personalized: the arm extension and retraction range to manipulate the distance via the "force-control" mechanism (A_{dist}), the arm vertical movement range to control the origin (A_{ori}), and the wrist upward/extension and downward/flexion range to control the launch angle (W_{angle}). For each of these ranges, the user might have more or less control and stability over their movements in the beginning of the range, the middle of the range, or the end of the range. We hence explore suitable sensitivity functions for each movement range. To evaluate their performance, especially for difficult to reach destinations, we run a final user study with the most promising curve combinations and test if using sensitivity curves provide any benefit in hands-only VR teleportation with PAW.

5.1 Sensitivity Functions

Beside linear mapping (study 1), we consider two other candidates and their inverse: quadratic (bell) and sigmoid.

- The **quadratic** function creates a mapping with a fine-grained control (less stable) control in the middle range and coarse control (more stable) controls near the extremes. On the opposite, the inverse quadratic function leads to a coarse control control in the middle range and fine-grained controls toward the extremes. Both the quadratic function and its inverse are *symmetric*, i.e. swapping low and high values would lead to the same results. The formula $y = -a\,(x-h)^2 + k$ can be used to map the pointer movement sensitivity between a range of 0 to 100, for any input x, where the mapped output sensitivity is y. Here ‘a’ defines a quarter of the full range, ‘h’ defines the midpoint and ‘k’ defines the max of the range. The constants a, h, and k can be fine-tuned based on the context: For a sensitivity range between 0 to 100, we used a = 1/25, h = 50 and k = 100.
- The **sigmoid** function creates a mapping with fine-grained control (less stable) for low values, and with coarse control (more stable) for the higher range. On the opposite, the inverse sigmoid function creates a mirrored mapping. Thus, the sigmoid functions are *asymmetric.* The formula $y = \frac{100}{1+e^{p-cx}}$ can be used to map the pointer movement sensitivity between a range of 0 to 100, for any input x where the mapped output sensitivity is y. Similar to the quadratic mapping, the constants p and c can be optimized based on the implementation whereas in our implementation, we used c = 0.1, p = 5 and k = 100. Here ‘c’, ‘p’ determines the midpoint of the sensitivity range, larger values move the midpoint higher, and lower values move the midpoint lower. Our values put it at the exact midpoint. The formula can also be solved for x, to get the inverse Sigmoid sensitivity.

5.2 Association Between Motor Movements and Sensitivity Functions

5.2.1 Arm Movements. Teleporting to destinations that are especially higher, lower or distant require far arm horizontal extension (A_{dist}) and high arm vertical movement (A_{ori}). Previous work by Ramos et al. [24] have shown that when the arm is higher or farther from its resting position near the body, movements take more effort and torque whereas center position are optimal for interaction. We hypothesize that this also applies in our context with users having less stability and control when the arm is extended far or high up. This is supported by our observations during the first study: when the arm was close to the body, users rested their elbow on their torso to enhance their arm stability and control. However, when the arm is extended or higher up, users do not have this extra support. Consequently, we consider arm movements as asymmetric and exclude symmetric functions (i.e., quadratic). We hence explore the two sigmoid and inverse-sigmoid functions with arm as shown in Figure 5a.

5.2.2 Wrist Movement. Teleporting to-and-from higher destinations requires large wrist upward/extension and downward/flexion angles (W_{angle}). As flexibility and stability of the wrist can differ based on the angle of the wrist, some positions may be harder to hold stable. We observed in our previous study that for high destinations, users typically perform very steep wrist angles. Previous work [41] showed that symmetric quadratic sensitivity curves work the best for wrist movement as the middle range of W_{angle} is more steady than extreme angles. We hence use a symmetric quadratic sensitivity curve for the wrist movement, so that extreme angles benefit from a more stable (coarse) control than the middle range (Figure 5e).

5.3 Evaluated Techniques

Mapping sensitivity functions (i.e., four functions: quadratic and sigmoid and their inverse variants) with arm (A_{dist} and A_{ori}) and wrist movements (W_{angle}) leads to $4\times4\times4 = 64$ combinations. However, investigating all these combinations with a study is practically unfeasible. Therefore, we decided on the combinations based on a pilot study and prior work related to mapping sensitivity functions to motor controls. In the pilot study (N=4), we only used four sensitivity functions (i.e., quadratic and sigmoid and their inverse variants) to map with arm (A_{dist} and A_{ori}) and wrist movements (W_{angle}). We used the same teleportation tasks as in Study 1 where participants were required to teleport to a platform. However, we only investigated difficult conditions: 10.5 m distance, and height variations from 0 m to 5 m and from 5 m to 0 m conditions. During the pilot study, we observed that quadratic functions works better for wrist movement mapping, and sigmoid or inverse sigmoid functions are more suitable than others for arm movement mapping. Interestingly, we observed that participants' performance degraded when using two different functions for A_{dist} and A_{ori}. Therefore, we came up with the following techniques consisting of PAW with added sensitivity functions (i.e. PAWS+S where S = SSQ, IIQ, SIQ, ISQ). Names are given only based on the sensitivity function initials for the sake of brevity. Note that for all the techniques except for PAW, we used a quadratic function to map wrist angles (W_{angle}) to the pointer movements.

- **PAW**: PAW involves linear functions to remap all movements - the arm horizontal extension (A_{dist}), the arm vertical movement (A_{ori}), and the wrist angles (W_{angle}) to control the parabolic pointer movement.
- **SSQ** (Sigmoid-Sigmoid-Quadratic): SSQ uses the same Sigmoid function for both the horizontal arm extension (A_{dist}) and the vertical arm movement (A_{ori}). We anticipate that SSQ can provide less sensitivity (high degree of stabilization and control of the pointer) when the arm is high and/or extended, and more sensitivity when the arm is low or near the user's body (Figure 5a, b).
- **IIQ** (Inverse Sigmoid-Inverse Sigmoid-Quadratic): IIQ uses an inverse sigmoid function for both the horizontal arm extension (A_{dist}) and the vertical arm movement (A_{ori}). This technique would allow users to rapidly move the pointer with more sensitivity when the arm is high and far, and the inverse when the arm is near or low (Figure 5a, c).
- **SIQ** (Sigmoid-Inverse Sigmoid-Quadratic): SIQ uses a sigmoid function for the horizontal arm extension (A_{dist}) and an inverse sigmoid function for the vertical arm movement (A_{ori}). With this technique, users have a less sensitive pointer (i.e., more stabilization) when the arm is low and far, and the inverse when it is high and close (Figure 5a).
- **ISQ** (Inverse Sigmoid-Sigmoid-Quadratic): This mapping - the opposite of SIQ - uses an inverse sigmoid function for the horizontal arm extension (A_{dist}), and a sigmoid function for the vertical arm movement (A_{ori}). ISQ would offer users less sensitive pointers (i.e., more stabilization) when the arm is high and close, and the inverse when the arm is low and far (Figure 5a).

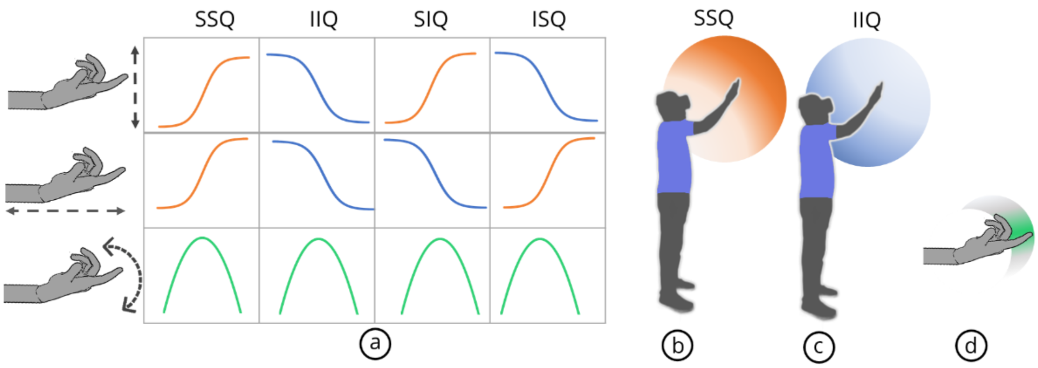

Fig. 5. (a) The sensitivity curves for each motor movement. Appearing left to right in sequence: SSQ, IIQ, SIQ and ISQ. (b-d) The result of the sensitivity curve combinations is shown with gradients. A stronger color in the gradient indicates higher stability (i.e., coarse movements), and a weaker color indicates lower stability (i.e., fine-grained movements). Note that the effect for arm movement (A_{dist} and A_{ori}) is only shown in (b) SSQ and (c) IIQ, excluding the wrist movement (W_{angle}). (d) Wrist uses a quadratic function where upward/extension and downward/flexion extreme angles benefit from a more stable control than the middle range.

5.4 Participants

Fifteen right-handed participants (mean age = 25.1, SD = 4.04, mean height = 163.7, SD = 6.18, 5 females), between the age 19 and 32 were recruited from a local university using on-campus flyers and word-of-mouth. Participants were compensated with a $15 gift card for their participation. Eleven participants had prior experience using VR applications. None of them participated in the first study.

5.5 Experimental Tasks, Procedure, and Design

5.5.1 Task. We use the same teleportation tasks described in Study 1 where participants were required to teleport to a platform marked with a semi-transparent sphere. However, we made some changes in *Distance* and *Height variation* to focus on difficult situations. Study 1 revealed that participants were significantly slower when the target platforms were located far and when they were required to teleport to high upward or downward trajectories. We hence keep only distant targets (7.5 m and 11.5 m), and 3 height variations (from 0 m to 0 m, upward from 0 m to 5 m, and downward from 5 m to 0 m).

5.5.2 Procedure. The study starts with similar briefing and settings to study 1. First, 30 practice trials are given so that participants could familiarize themselves with VR teleportation without any personalization technique (baseline condition for study 1). After the 30 generic trials, participants started the experiment using each evaluated technique. They completed 15 practice trials before starting each new technique, with a 2-minute break in-between to avoid arm fatigue. Each participant completed 2 *Distance* × 3 *Height variation* × 2 blocks × 5 repetitions for each technique = 60 trials for each *Technique*. Participants had a 1-minute break between the two blocks of trials, and another 2-minute break in-between technique. Once participants completed all trials, they filled out a questionnaire to provide feedback on each *Technique*. A session lasted approximately 60 minutes including short breaks and practice trials.

5.5.3 Study Design. The study used a 5×2×3 within-subjects design for factors *Technique* (PAW, SSQ, IIQ, SIQ, ISQ), *Distance* (7.5 m and 11.5 m), and *Height variation* (from 0 m to 0 m, upward from 0 m to 5 m, and downward from 5 m to 0 m). With 2 blocks of 5 repetitions, each participant performed a total of 300 trials. The order of *Technique* was counter-balanced between participants and *Distance* and *Height variation* were presented in a random order for each technique. We logged *Trial Time* and *Error Rate* where the *Trial Time* is measured by the time a user took to teleport from the current position to the target location. *Error Rate* is defined by the number of times the user attempted to teleport to a non-target destination. We also collected subjective feedback on techniques via questionnaires.

5.6 Results

5.6.1 Trial time. We analyze log-transformed trial time with repeated measures ANOVA and post-hoc pairwise comparisons with Bonferroni corrections. *Technique* has significant effects on trial time ($F_{4,41} = 4.11$, $p < 0.01$, $\eta^2 = 0.23$). The mean trial times are 2.96s ([2.84, 3.01]) for PAW, 2.71s ([2.61, 2.81]) for SSQ, 2.72s ([2.61, 2.83]) for IIQ, 2.97s ([2.83, 3.11]) for SIQ, and 2.88s ([2.76, 2.99]) for ISQ. Post-hoc pairwise comparisons reveal that SSQ and IIQ are significantly faster than PAW (both $p < 0.001$, Cohen's d 0.45, Cohen's d 0.42, respectively), SIQ (both $p < 0.01$, Cohen's d 0.46, Cohen's d 0.43, respectively), and ISQ (both $p < 0.01$, Cohen's d 0.33, Cohen's d 0.30, respectively). No other statistically significant differences between the techniques were observed. Results show that *Height variation* ($F_{2,41} = 59.00$, $p < 0.001$, $\eta^2 = 0.81$) and *Distance* ($F_{1,41} = 87.59$, $p < 0.001$, $\eta^2 = 0.86$) have also a significant effect on trial time. Post-hoc pairwise comparisons show differences between all height variation pairs and between the two distances: Participants are faster when teleporting to close targets (mean = 2.66s [2.59, 2.74]) or without height difference (mean = 2.63s [2.54, 2.71]) than when teleporting to distant (mean = 3.03s [2.96, 3.10], Cohen's d 0.65) or elevated locations (mean = 3.11s [3.02, 3.20], Cohen's d 0.87). While there is no significant interaction effect between *Technique* and *Distance* ($F_{4,41} = 2.40$, $p = 0.06$), results show interesting interaction effects between *Technique* and *Height variation* ($F_{8,41} = 2.25$, $p < 0.05$, $\eta^2 = 0.14$) - although with a small effect size. There are significant differences between every *Height variation* for every technique (all $p < 0.05$) except for SSQ and IIQ. Indeed, with IIQ, trial time is resistant to height variation for the two first levels (mean = 2.45s [2.28, 2.62] and 2.63s [2.45, 2.83]) ($p > 0.05$), and different only with the largest height variation (mean = 3.06s [2.92, 3.21]) compared to the two smaller variations ($p < 0.001$). SSQ shows another trend: the smallest height variation (mean = 2.58s [2.34, 2.77]) leads to faster trial times than with larger variations (mean = 2.72s [2.68, 2.98] and 2.83s [2.57, 2.88]) ($p > 0.05$), but there is no effect on trial time between the two larger variations ($p > 0.5$). Thus, with none or

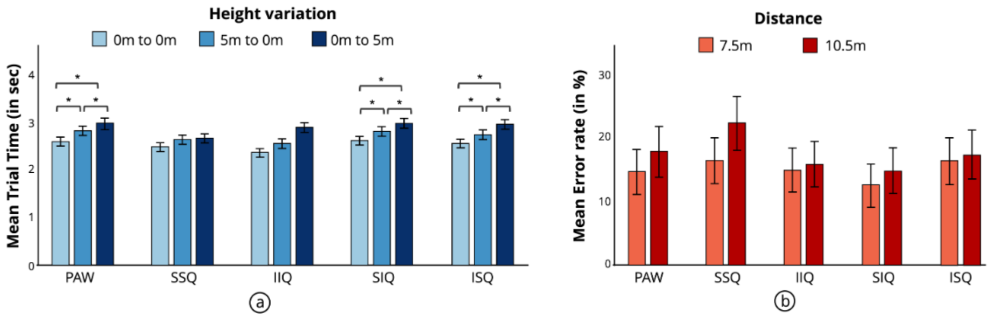

Fig. 6. Mean (a) trial time across the techniques for different height variations and (b) error rate across the techniques for different distances. Error bars show the 95% CIs.

small height variations, only IIQ leads to significantly faster trial times than PAW ($p < 0.05$), while with large height variations, only SSQ is significantly faster than PAW, SIQ, and ISQ (all $p < 0.05$).

5.6.2 Error Rate. We analyze error rate with Friedman tests with Wilcoxon tests for post-hoc pairwise comparisons. The overall error rate is 16.1%. There is no significant difference in error rates regarding *Technique* ($\chi^2(4, N = 15) = 5.92, p = 0.21$), *Height variation* ($\chi^2(2, N = 15) = 1.73, p = 0.42$), and *Distance* ($z = -1.48, p = .14$). Participants perform more errors when executing far (10.5m, mean = 18%, SD 0.70) and elevated (5m, mean = 16%, SD 0.72) teleportation.

5.6.3 Preference Scores and Subjective Feedback. Similar to study 1, we collected users feedback on their preference, fatigue, speed, accuracy and easiness on a 5-point Likert scale for each technique. We analyze the data with Wilcoxon Signed Ranked Tests. We observe that *Technique* has no significant effect on users' preference ($\chi^2(4, N = 15) = 3.51, p = 0.48$), fatigue ($\chi^2(4, N = 15) = 5.83, p = 0.21$), speed ($\chi^2(4, N = 15) = 5.64, p = 0.23$), accuracy ($\chi^2(4, N = 15) = 5.13, p = 0.27$), and easiness ($\chi^2(2, N = 15) = 10.78, p = 0.04$). There is no other pairwise statistically significant differences.

Feedback from participants reveals that two preferred IIQ than other techniques. One participant mentioned, *"[I] especially liked IIQ as it felt like I could move the pointer without trying to hold my hand steady"* [P3]. Another participant commented that *"IIQ helped me with my shaky hands, and It was hard with other techniques, especially with the target located at a high elevation"* [P5]. Participants also identified SIQ as a difficult technique for teleportation. One participant expressed that *"SIQ was a very hard technique for high targets"* [P4]. They also noticed that some techniques helped them reach close targets. One participant commented *"For the ISQ and baseline techniques, my accuracy was high when the targets were located at a closer distance"* [P6].

5.7 Discussion

RQ2: *How should the personalization of motor movements be remapped to the personalized motor ranges?*
We observed that using sensitivity functions to counteract the reduction of stability while offering more control for teleporting to distant and elevated targets results in faster performance for SSQ and IIQ. Our hypothesis that using an asymmetric sensitivity function that provided more coarse control for such targets would result in better performance for high targets was also proven correct as SSQ provided the best performance. As such, the sensitivity functions were demonstrated to be a valuable addition to the full personalization option. PAWS (PAW + Sensitivity Functions) provides an improved bare-handed teleportation experience. However, IIQ, the mirror opposite of SSQ, also improved performance users' teleportation performance. We observed that this is primarily due to the lower *Height variation* (e.g., from 0 m to 0 m) and near *Distance* (e.g., 7.5 m) used in the study.

Interestingly, We also observed that SIQ and ISQ didn't perform better than PAW, and worse than SSQ and IIQ. Note that SIQ and ISQ used opposite sensitivity functions for arm movements, i.e., the horizontal arm extension (A_{dist}) and the vertical arm movement (A_{ori}). This suggests avoiding using dissimilar sensitivity functions for closely coupled motor movements.

6 DESIGN CONSIDERATIONS

We interpret key insights from our results and provide the main takeaways.

- **Consider Full Personalization** (from study 1): In controller-based games (e.g., joystick-based video games), users commonly **control virtual characters** offering the same abilities to every user regardless of users' physical attributes. However, in virtual reality, users commonly **are the characters** in the virtual environment, and their physical attributes such as height and arm length, can result in different experiences due to differences. We hence advise a fully personalized (i.e., PAWS) teleportation technique for significantly faster performance than partial (e.g., PAdist in our case) and no personalization (i.e., Baseline in our case). In addition, users' performance and subjective feedback also reflect that a fully personalized hands-only teleportation technique helps users with reduced arm movements and wrist flexion/extension abilities. Therefore, we suggest future researchers and developers to consider providing fully personalized VR applications, games, and interactions to provide better and equal experiences to users regardless of their physical attributes.

- **Use Sensitivity Functions For Hands-Only Teleportation** (from study 2): Consider using asymmetric sensitivity functions for arm movements and symmetric sensitivity functions for the wrist to counteract the reduction of performance in extreme poses, significantly improving users' performance for distant and elevated targets.
  - **Map Motor Profiles to Sensitivity Functions**: We suggest mapping asymmetric motor movements with asymmetric functions and symmetric motor movements with symmetric functions, also suggested in [26, 41].
  - **Combine Similar Sensitivity Functions For Connected Movements**: Using similar sensitivity functions for coupled movements (e.g., vertical and horizontal arm movements) provides better performance than using dissimilar functions. We suggest designers to avoid using dissimilar sensitivity function combinations for closely coupled motor movements as it decreases performance.
  - **Choose Suitable Sensitivity Function Combinations**: We observed in our context that using SSQ helped reduce the trial time for high and distant targets, whereas IIQ reduced the trial time for low and close targets. As such, designers should also consider context-based senstivity functions for teleportation tasks in VR environments.

7 LIMITATIONS AND FUTURE WORK

Our exploration of hands-only teleportation presents some limitations. For example, we focused primarily on controller-free teleportation and did not compare users' performance with physical controllers. A future study will explore similar limitations for controller-based teleportation as the parabola launch angle in controllers depends on the radial and ulnar deviation of the hand that holds the controller. Hand-based straight-line aiming for 3D Fitts law has been explored [25, 31]. Therefore, rather than focusing on Fitts law, we investigated personalization in the context of teleportation and kept our task design similar to previous work [11, 19, 34]. To avoid any interference with other hand gestures and hand-based interactions, dedicated and unique gestures could be used to enter or exit the teleportation system. We did not explore this in our work, but promising directions have been explored in prior work [11]. Even though PAWS provides faster performance than standard techniques, users were not able to reduce the relatively high error rate (around 15%) for hands-only teleportation. We attribute this high error rate to our difficult conditions (i.e., high and distant targets pushing the boundaries of the reachable area), this is still a notable limitation. Future work can explore precise selection methods to lower this error rate. Our studies had only 12 and 15 participants in study 1 and 2, respectively. This is a limitation, however similar sample sizes were frequently used in HCI research [8]. We acknowledge that the height parameters were based on North American averages. However, our participants covered a wide range of extension and retraction values. For instance, we noticed arm vertical ranges with shoulder height being the base (i.e., 0) position from -0.40m (SD 0.09) to 0.32m (SD 0.14), arm horizontal ranges from 0.19m (SD 0.37) to 0.51m (SD 0.06), wrist extension and flexion ranges from +61° (SD 11.1) to -68° (SD 2.9). In the future, studies could focus more exclusively on body-related measures as experimental factors to further validate the effectiveness of personalization techniques. We only explored a limited combination of sensitivity curves by reviewing previous works and running pilots, thus excluding an exhaustive investigation of all possible combinations. Future studies can be conducted by incorporating more combinations. Our task design did not consider any occlusions or obstacles that might typically be present in realistic navigation tasks in 3D environments. We also did not include multiple teleportation steps and other pointer types (e.g., straight line pointer). A straight line pointer has been shown to have advantages for mid-air targets [34], its effectiveness to platform based destinations, specially with and without personalization can be explored in a future study. Given that our work represents one of the early studies exploring the factors relevant to personalized teleportation, other key issues related to teleportation, such as occlusions, obstacles, multiple teleportations, and different pointer types can be explored as possible future work.

In future, we aim to explore our controller-free navigation techniques for VR navigation on smartphones. Wrist motions can we observed through the smartphone camera and can be adapted to shift the user's view in 3D space. Similarly, mobility is essential for a number of VR applications, such as gaming or rehabilitation. We aim to explore means of integrating our devised teleportation approach with common navigation interfaces. Finally, with recent developments, we envision Mixed Reality interfaces that allow rapid navigation in virtual environments to support tasks in the physical space. For example, for maintenance and repair, an application can allow the user to switch to a VR environment wherein they can teleport between different instruction sets that are laid out in the 3D virtual environment.

8 CONCLUSION

In this paper, we investigated hands-only personalized teleportation techniques considering users' attributes, such as arm movement and wrist flexibility ranges. We first conducted a study exploring personalized teleportation techniques while varying the degree of personalization. Results showed that a higher degree of personalization improves user performance with teleportation - however, the performance degraded for high and distant targets due to reduced motor stability and control. We conducted a second study to further investigate these motor range boundaries issues. More precisely, we investigated different sensitivity functions for hands-only personalized teleportation. We found that asymmetric functions for arm movements and symmetric functions for wrist extension/flexion improved users' performance in reaching high and distant targets, thus assisting in human motor abilities for teleportation. To conclude, Personalized Arm and Wrist Movements with Sensitivity functions (PAWS) provides users with an enhanced teleportation experience and should be considered for designing future bare-handed VR techniques.

9 ACKNOWLEDGEMENTS

We thank all the participants for their time and feedback. This research was partially funded by a Natural Sciences and Engineering Research Council (NSERC) grants RGPIN-2019-05211 and CREATE-555398-2021.

REFERENCES

[1] Ofer Arazy, Oded Nov, and Nanda Kumar. 2015. Personalityzation: UI personalization, theoretical grounding in HCI and design research. *AIS Transactions on Human-Computer Interaction* 7, 2 (2015), 43–69.

[2] Tomislav Bezmalinovic. 2022. Cambria: Meta's high-end headset launches without Controller - Report. (2022). Retrieved September 15, 2022 from https://mixed-news.com/en/cambria-metas-high-end-headset-launches-without-controller-report/.

[3] Costas Boletsis and Jarl Erik Cedergren. 2019. VR locomotion in the new era of virtual reality: an empirical comparison of prevalent techniques. *Advances in Human-Computer Interaction* 2019 (2019).

[4] Benjamin Bolte, Frank Steinicke, and Gerd Bruder. 2011. The jumper metaphor: an effective navigation technique for immersive display setups. In *Proceedings of Virtual Reality International Conference*, Vol. 1.

[5] Evren Bozgeyikli, Andrew Raij, Srinivas Katkoori, and Rajiv Dubey. 2016a. Locomotion in virtual reality for individuals with autism spectrum disorder. In *Proceedings of the 2016 Symposium on Spatial User Interaction*. 33–42.

[6] Evren Bozgeyikli, Andrew Raij, Srinivas Katkoori, and Rajiv Dubey. 2016b. Point & Teleport Locomotion Technique for Virtual Reality. In *Proceedings of the 2016 Annual Symposium on Computer-Human Interaction in Play (CHI PLAY '16)*. Association for Computing Machinery, New York, NY, USA, 205–216. DOI: http://dx.doi.org/10.1145/2967934.2968105

[7] W. Broll, I. Lindt, J. Ohlenburg, I. Herbst, M. Wittkamper, and T. Novotny. 2005. An infrastructure for realizing custom-tailored augmented reality user interfaces. *IEEE Transactions on Visualization and Computer Graphics* 11, 6 (2005), 722–733. DOI: http://dx.doi.org/10.1109/TVCG.2005.90

[8] Kelly Caine. 2016. Local Standards for Sample Size at CHI *(CHI '16)*. Association for Computing Machinery, New York, NY, USA. DOI: http://dx.doi.org/10.1145/2858036.2858498

[9] Jeff Chastine, Nicole Kosoris, and Joshua Skelton. 2013. A study of gesture-based first person control. In *Proceedings of CGAMES'2013 USA*. IEEE, 79–86.

[10] Heni Cherni, Natacha Métayer, and Nicolas Souliman. 2020. Literature review of locomotion techniques in virtual reality. *International Journal of Virtual Reality* (2020).

[11] Sohan Chowdhury, A K M Amanat Ullah, Nathan Bruce Pelmore, Pourang Irani, and Khalad Hasan. 2022. WriArm: Leveraging Wrist Movement to Design Wrist+Arm Based Teleportation in VR. In *2022 IEEE International Symposium on Mixed and Augmented Reality (ISMAR)*. 317–325. DOI: http://dx.doi.org/10.1109/ISMAR55827.2022.00047

[12] Chris G Christou and Poppy Aristidou. 2017. Steering versus teleport locomotion for head mounted displays. In *International conference on augmented reality, virtual reality and computer graphics*. Springer, 431–446.

[13] Jacob Cohen and others. 1965. Some statistical issues in psychological research. *Handbook of clinical psychology* (1965), 95–121.

[14] NCD Risk Factor Collaboration and others. 2016. A century of trends in adult human height. *Elife* 5 (2016), e13410.

[15] Noah Coomer, Sadler Bullard, William Clinton, and Betsy Williams-Sanders. 2018. Evaluating the Effects of Four VR Locomotion Methods: Joystick, Arm-Cycling, Point-Tugging, and Teleporting. In *Proceedings of the 15th ACM Symposium on Applied Perception (SAP '18)*. Association for Computing Machinery, New York, NY, USA, Article 7, 8 pages. DOI: http://dx.doi.org/10.1145/3225153.3225175

[16] Andrea Ferracani, Daniele Pezzatini, Jacopo Bianchini, Gianmarco Biscini, and Alberto Del Bimbo. 2016. Locomotion by Natural Gestures for Immersive Virtual Environments. In *Proceedings of the 1st International Workshop on Multimedia Alternate Realities (AltMM '16)*. Association for Computing Machinery, New York, NY, USA, 21–24. DOI: http://dx.doi.org/10.1145/2983298.2983307

[17] Eelke Folmer, Isayas Berhe Adhanom, and Aniruddha Prithul. 2021. Teleportation in Virtual Reality; A Mini-Review. *Frontiers in Virtual Reality* (2021), 138.

[18] Julian Frommel, Sven Sonntag, and Michael Weber. 2017. Effects of Controller-Based Locomotion on Player Experience in a Virtual Reality Exploration Game. In *Proceedings of the 12th International Conference on the Foundations of Digital Games (FDG '17)*. Association for Computing Machinery, New York, NY, USA, Article 30, 6 pages. DOI: http://dx.doi.org/10.1145/3102071.3102082

[19] Markus Funk, Florian Müller, Marco Fendrich, Megan Shene, Moritz Kolvenbach, Niclas Dobbertin, Sebastian Günther, and Max Mühlhäuser. 2019. Assessing the Accuracy of Point & Teleport Locomotion with Orientation Indication for Virtual Reality Using Curved Trajectories. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. Association for Computing Machinery, New York, NY, USA, 1–12. DOI: http://dx.doi.org/10.1145/3290605.3300377

[20] Martin Gonzalez-Rodriguez, Jorge Manrubia, Agueda Vidau, and Marcos Gonzalez-Gallego. 2009. Improving accessibility with user-tailored interfaces. *Applied Intelligence* 30, 1 (2009), 65–71. DOI: http://dx.doi.org/10.1007/s10489-007-0098-3

[21] Martín González Rodríguez, J Ramón Pérez Pérez, and M Paule Ruíz. 2004. Designing user interfaces tailored to the current user's requirements in real time. In *International Conference on Computers for Handicapped Persons*. Springer, 69–75.

[22] Khalad Hasan, David Ahlström, and Pourang Irani. 2013. Ad-binning: leveraging around device space for storing, browsing and retrieving mobile device content. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. 899–908.

[23] Khalad Hasan, David Ahlström, Junhyeok Kim, and Pourang Irani. 2017. Airpanes: Two-handed around-device interaction for pane switching on smartphones. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems*. 679–691.

[24] Juan David Hincapié-Ramos, Xiang Guo, Paymahn Moghadasian, and Pourang Irani. 2014. Consumed Endurance: A Metric to Quantify Arm Fatigue of Mid-Air Interactions *(CHI '14)*. Association for Computing Machinery, New York, NY, USA, 1063–1072. DOI: http://dx.doi.org/10.1145/2556288.2557130

[25] Errol R Hoffmann, Colin G Drury, and Carol J Romanowski. 2011. Performance in one-, two-and three-dimensional

terminal aiming tasks. *Ergonomics* 54, 12 (2011), 1175–1185.

[26] Juan Pablo Hourcade, Christopher M Nguyen, Keith B Perry, and Natalie L Denburg. 2010. Pointassist for older adults: analyzing sub-movement characteristics to aid in pointing tasks. In *Proceedings of the sigchi conference on human factors in computing systems*. 1115–1124.

[27] Rachel Huang, Carisa Harris-Adamson, Dan Odell, and David Rempel. 2019. Design of finger gestures for locomotion in virtual reality. *Virtual Reality & Intelligent Hardware* 1, 1 (2019), 1–9.

[28] Maryam Khademi, Hossein Mousavi Hondori, Alison McKenzie, Lucy Dodakian, Cristina Videira Lopes, and Steven C Cramer. 2014. Free-hand interaction with leap motion controller for stroke rehabilitation. In *CHI'14 Extended Abstracts on Human Factors in Computing Systems*. 1663–1668.

[29] Mohamed Khamis, Daniel Buschek, Tobias Thieron, Florian Alt, and Andreas Bulling. 2018. EyePACT: Eye-Based Parallax Correction on Touch-Enabled Interactive Displays. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 1, 4, Article 146 (jan 2018), 18 pages. `DOI:`http://dx.doi.org/10.1145/3161168

[30] Chaowanan Khundam. 2015. First person movement control with palm normal and hand gesture interaction in virtual reality. In *2015 12th International Joint Conference on Computer Science and Software Engineering (JCSSE)*. IEEE, 325–330.

[31] Alexander Kulik, André Kunert, and Bernd Froehlich. 2020. On motor performance in virtual 3d object manipulation. *IEEE transactions on visualization and computer graphics* 26, 5 (2020), 2041–2050.

[32] Aqueasha Martin-Hammond, Abdullah Ali, Catherine Hornback, and Amy K. Hurst. 2015. Understanding Design Considerations for Adaptive User Interfaces for Accessible Pointing with Older and Younger Adults. In *Proceedings of the 12th International Web for All Conference (W4A '15)*. Association for Computing Machinery, New York, NY, USA, Article 19, 10 pages. `DOI:`http://dx.doi.org/10.1145/2745555.2746645

[33] Aqueasha Martin-Hammond, Foad Hamidi, Tejas Bhalerao, Christian Ortega, Abdullah Ali, Catherine Hornback, Casey Means, and Amy Hurst. 2018. Designing an adaptive web navigation interface for users with variable pointing performance. In *Proceedings of the 15th International Web for All Conference (W4A '18)*. Association for Computing Machinery, New York, NY, USA, Article 31, 10 pages. `DOI:`http://dx.doi.org/10.1145/3192714.3192818

[34] Andrii Matviienko, Florian Müller, Martin Schmitz, Marco Fendrich, and Max Mühlhäuser. 2022. SkyPort: Investigating 3D Teleportation Methods in Virtual Environments. In *CHI Conference on Human Factors in Computing Systems (CHI '22)*. Association for Computing Machinery, New York, NY, USA, Article 516, 11 pages. `DOI:`http://dx.doi.org/10.1145/3491102.3501983

[35] Mark R Mine. 1995. Virtual environment interaction techniques. *UNC Chapel Hill CS Dept* (1995).

[36] MRTK2. 2022. MRTK2-Unity Developer Documentation - MRTK 2. (2022). Retrieved September 15, 2022 from https://docs.microsoft.com/en-us/windows/mixed-reality/mrtk-unity/mrtk2/?view=mrtkunity-2022-05.

[37] Oculus. 2022. Oculus Developer Center. (2022). Retrieved September 15, 2022 from https://developer.oculus.com/.

[38] Yun Suen Pai and Kai Kunze. 2017. Armswing: Using arm swings for accessible and immersive navigation in ar/vr spaces. In *Proceedings of the 16th International Conference on Mobile and Ubiquitous Multimedia*. 189–198.

[39] Laxmi Pandey, Khalad Hasan, and Ahmed Sabbir Arif. 2021. Acceptability of Speech and Silent Speech Input Methods in Private and Public. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*. 1–13.

[40] Octavian Postolache, Luís Teixeira, João Cordeiro, Luísa Lima, Patrícia Arriaga, Mariana Rodrigues, and Pedro Girão. 2019. Tailored Virtual Reality for Smart Physiotherapy. In *2019 11th International Symposium on Advanced Topics in Electrical Engineering (ATEE)*. 1–6. `DOI:`http://dx.doi.org/10.1109/ATEE.2019.8724903

[41] Mahfuz Rahman, Sean Gustafson, Pourang Irani, and Sriram Subramanian. 2009. Tilt Techniques: Investigating the Dexterity of Wrist-Based Input. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems (CHI '09)*. Association for Computing Machinery, New York, NY, USA, 1943–1952. `DOI:`http://dx.doi.org/10.1145/1518701.1518997

[42] SL Reeves, C Varakamin, and CJ Henry. 1996. The relationship between arm-span measurement and height with special reference to gender and ethnicity. *European journal of clinical nutrition* 50, 6 (June 1996), 398—400. http://europepmc.org/abstract/MED/8793422

[43] RogPodge. 2022. Teleport system - MRTK 2. (2022). Retrieved September 15, 2022 from https://docs.microsoft.com/en-us/windows/mixed-reality/mrtk-unity/mrtk2/features/teleport-system/teleport-system?view=mrtkunity-2022-05.

[44] Alexander Schäfer, Gerd Reis, and Didier Stricker. 2021. Controlling teleportation-based locomotion in virtual reality with hand gestures: a comparative evaluation of two-handed and one-handed techniques. *Electronics* 10, 6 (2021), 715.

[45] Martin Usoh, Kevin Arthur, Mary C. Whitton, Rui Bastos, Anthony Steed, Mel Slater, and Frederick P. Brooks. 1999. Walking > Walking-in-Place > Flying, in Virtual Environments. In *Proceedings of the 26th Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH '99)*. ACM Press/Addison-Wesley Publishing Co., USA, 359–364. `DOI:`http://dx.doi.org/10.1145/311535.311589

[46] Valve. 2022a. Half-Life: Alyx on Steam. (2022). Retrieved September 15, 2022 from https://store.steampowered.com/app/546560/HalfLife_Alyx/.

[47] Valve. 2022b. SDK Installation - Valve Developer Community. (2022). Retrieved September 15, 2022 from https:

//developer.valvesoftware.com/wiki/SDK_Installation.

[48] VIVE. 2022. VIVE Focus 3 - VR Headset for Metaverse Solutions. (2022). Retrieved September 15, 2022 from https://www.vive.com/us/product/vive-focus3/overview/.

[49] Julius von Willich, Martin Schmitz, Florian Müller, Daniel Schmitt, and Max Mühlhäuser. 2020. Podoportation: Foot-Based Locomotion in Virtual Reality. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–14. DOI: http://dx.doi.org/10.1145/3313831.3376626

[50] Dennis Wolf, Jan Gugenheimer, Marco Combosch, and Enrico Rukzio. 2020. Understanding the Heisenberg Effect of Spatial Interaction: A Selection Induced Error for Spatially Tracked Input Devices. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20)*. Association for Computing Machinery, New York, NY, USA, 1–10. DOI: http://dx.doi.org/10.1145/3313831.3376876

[51] Fan Zhang, Shaowei Chu, Ruifang Pan, Naye Ji, and Lian Xi. 2017. Double hand-gesture interaction for walk-through in VR environment. In *2017 IEEE/ACIS 16th International Conference on Computer and Information Science (ICIS)*. IEEE, 539–544.

Received January 2023; revised May 2023; accepted June 2023